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Twenty years of conservation tillage research in subarctic Alaska II. Impact on soil hydraulic properties

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Abstract

Soil management practices are needed in the subarctic that stabilize the soil against the forces of wind and water as well as conserve soil water for crop production. There is a paucity of information, however, regarding the long-term effects of conservation tillage on soil hydraulic properties in subarctic Alaska. The objective of this study was therefore to characterize infiltration, water retention, and saturated hydraulic conductivity of a soil 20 years after establishing tillage and straw management treatments in interior Alaska. The strip plot experimental design, established on a silt loam and maintained in continuous barley (*Hordeum vulgare* L.), included tillage as the main treatment and straw management as the secondary treatment. Tillage treatments included no tillage, autumn chisel plow, spring disk, and intensive tillage (autumn and spring disk) while straw treatments included retaining or removing stubble and loose straw from the soil surface after harvest. Soil properties were measured after sowing in spring 2004; saturated hydraulic conductivity was measured by the falling-head method, infiltration was measured using a double-ring infiltrometer, and water retention was assessed by measuring the temporal variation in in-situ soil water content. No tillage resulted in greater saturated hydraulic conductivity and generally retained more water against gravitational and matric forces than other tillage treatments. Infiltration was greater in autumn chisel plow than other tillage treatments and was presumably suppressed in no tillage by an organic layer overlying mineral soil. Infiltration was also enhanced by retaining straw on rather than removing straw from the soil surface after harvest. No tillage is not yet a sustainable management practice in this region due to lack of weed control strategies. In addition, the formation of an organic layer in no tillage has important ramifications for the soil hydrological and thermal environment. Therefore, minimum tillage (i.e., autumn chisel plow or spring disk) appears to be a viable management option for maximizing infiltration in interior Alaska.

Keywords: Infiltration; Soil water retention; Soil water; Hydraulic conductivity

1. Introduction

Small grain crops (e.g., barley) are well adapted to the interior region of Alaska. Lack of precipitation during spring, however, can create water stresses as plants develop throughout the spring and summer. Indeed, limited water is a main determinant of crop production in the region (Sharratt et al., 2003). Lack of precipitation, in conjunction with spring tillage and sowing operations, may also create soil surface conditions susceptible to wind erosion. Agricultural lands in parts of interior Alaska are generally characterized by soils that are moderately to severely susceptible to wind erosion (Knight et al., 1979; Siddoway et al., 1984).

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Tillage and crop residue management can alter the physical matrix and thus the hydraulic properties of soils. Studies conducted in more temperate regions other than the subarctic suggest that soils are wetter (Lafond et al., 1992; Arshad et al., 1995) and retain more water at a given matric potential (Allmaras et al., 1977; Mahboubi et al., 1993) when subject to no tillage as compared with conventional tillage practices. Soils managed using no tillage have been found to have a higher (Mielke et al., 1984; Mahboubi et al., 1993) as well as lower hydraulic conductivity (Datiri and Lowery, 1991) as compared with soils managed using minimum or conventional tillage. These contrasting responses in hydraulic conductivity to tillage practices are also evident in infiltration. For example, infiltration has been found to be slower in soils subject to no tillage as compared with conventional tillage practices because soils subject to no tillage can be denser or be less prone to crust disruption (Lindstrom et al., 1984; Freebairn et al., 1989). Other investigators, however, have found that infiltration is higher in soils subject to no tillage as compared with conventional tillage practices (Mielke et al., 1984; Dao, 1993). Infiltration, as well as water retention of soil, can also be enhanced by the addition of straw to the soil (Barzegar et al., 2002).

There are but a few studies that have examined the impact of long-term tillage and crop residue management on soil hydraulic properties. Twenty-eight years after establishing tillage treatments on a silt loam in Ohio, Mahboubi et al. (1993) found that no tillage resulted in a higher saturated hydraulic conductivity and greater water retention as compared with conventional tillage. Chang and Lindwall (1989) did not observe any change in saturated hydraulic conductivity and water retention of a clay loam 20 years after establishing tillage treatments in Alberta, but they did find that infiltration was greater for no tillage versus conventional tillage. Arshad et al. (1999) found infiltration and water retention of a silt loam was greater after about 12 years of no tillage versus conventional tillage in northern British Columbia. In contrast to the above studies, Heard et al. (1988) found that saturated hydraulic conductivity of a silty clay loam was higher when subject to 10 years of tillage than no tillage in Indiana. They attributed the higher conductivity of tilled soil to larger or a greater number of voids and cracks caused by the tillage implement.

Studies that document the effect of long-term tillage and crop residue management on soil hydraulic properties are even rarer in the subarctic. Sharratt (1996) found in one such study that a silt loam retained more water and had a higher saturated conductivity after being subject to seven years of no tillage compared with intensive tillage in interior Alaska. We are unaware of other long-term studies that have examined the influence of tillage and residue management on the physical properties of subarctic soils, thus the purpose of this study was to characterize soil hydraulic properties 20 years after establishing tillage and straw management treatments in interior Alaska.

2. Materials and methods

This long-term tillage and crop residue management study was conducted at the University of Alaska Fairbanks Agriculture and Forestry Experiment Station located near Delta Junction, Alaska (63°N, 145°W). The research site was cleared of indigenous vegetation in 1979 and cropped to barley beginning in 1982. All tillage and straw management treatments were established by the autumn of 1983. The experimental design was strip plot with tillage as the main treatment and straw management as the secondary treatment. Tillage treatments included (1) intensive tillage in which the soil (coarse-silty over sandy or sandy-skeletal, mixed, non-acid Aquic Eutrocryept) was disked with an offset disk after harvest in the autumn and in the spring prior to sowing, (2) disking prior to sowing in the spring, (3) chisel plow after harvest in the autumn, and (4) no tillage. Straw treatments included (1) retaining stubble and loose straw on the soil surface and (2) removal of stubble and straw from the soil surface after harvest. Main plots (23 m $\times$ 120 m) were replicated three times and split to accommodate straw treatments.

Each year for the past 20 years, barley was sown in May using a 0.18 m double disk, press wheel drill and harvested in late August or early September using a combine equipped with a straw spreader. Fertilizer was applied at the time of sowing and broadleaf weeds were controlled using a post-emergence herbicide.

2.1. Soil properties

Soil hydraulic properties were measured after sowing (May 18) but prior to tillering of barley in 2004. Soil properties were assessed at this time of year due to the vulnerability of the soil to rapidly dry and erode. Indeed, little precipitation and the preponderance of strong winds in spring can contribute to soil drying and wind erosion. Soil properties were assessed between crop rows and wheel tracks at 10 locations within each plot.

Saturated hydraulic conductivity was determined by the falling head method (Klute and Dirksen, 1986). Soil core samples were extracted from the 0 to 50 mm depth using stainless steel tubing (70-mm diameter and 50-mm long). In the no tillage treatment, the organic layer (a viable canopy of moss underlain by fibric and hemic materials 10 mm in thickness) overlying mineral soil was removed by hand prior to inserting the tubes into the soil. The tubing was inserted into the soil until the upper edge of the tube was level with the soil surface; the tubing was then extracted by hand from the soil. The soil was trimmed level with the upper and lower edges of the tube and cheese cloth was wrapped around the lower edge to stabilize the bottom of the soil column. Soil core samples were allowed to soak for 24 h inside a 10-mm deep tray filled with water. A standpipe, constructed by mounting a graduated cylinder to a lid that is attached to one end of 70-mm diameter tubing, was then secured to the top of sample. This assembly was then placed on a wire mesh screen located on the bottom of a 200-mm deep pan. Water was slowly added to the pan to achieve a rise in the water level of about 0.05 mm s^{-1} until the sample was immersed. The standpipe was then filled with water, and after lowering the water level inside the pan (5 mm above the lower edge of the bottom of the soil core sample), the rate of fall of the water column inside the standpipe was measured three separate times.

Infiltration was measured using a double ring infiltrometer, which consisted of a 300-mm diameter plastic pipe centered over a 125-mm diameter pipe. Both the inner and outer pipes were inserted 50 mm into the soil (in the no tillage treatments, pipes were inserted 70 mm from the effective surface due the presence of an organic layer overlying the mineral soil surface). Soil water content was measured prior to infiltration using a TDR with 100 mm waveguides. The waveguides were installed vertically into the soil profile outside the area encompassed by the pipes. Water was then added to both the inner and outer pipe using a deflector to minimize splashing and disturbing the soil surface. Cumulative infiltration from the inner pipe was monitored for 45 min and then over an additional 15 min. Periodic assessments of infiltration during the course of this study indicated that steady state was achieved within 30 to 45 min for all treatments. In situ soil water retention was then assessed near the center of the infiltrometer by measuring the temporal change in water content in the upper 100 mm of the soil profile. Water content was measured at 0, 1, 6, 24, and 48 h after the water completely infiltrated the soil surface (water not visible on the soil surface). Evaporation from these infiltration sites was prevented by covering the soil surface with a 0.8 m^2 piece of plastic immediately after the infiltrometer was removed from the soil surface.

2.2. Statistical analysis

Analysis of variance was used to test for differences among treatments. Experimental data were analyzed using a strip plot design. In the event that significant F-values ($P \leq 0.05$) were found in analysis of variance, differences among treatments were separated using least significant difference (LSD).

3. Results and discussion

Soil properties can be manipulated by human activities (e.g., tillage) as well as influenced by biotic and climatic processes. Weather can directly affect soil properties as a result of forces exerted upon the soil matrix by raindrop impact or wetting and drying processes. The wet spring of 2004 likely influenced the soil hydraulic properties of this study as May 2004 ranked as one of the wettest since weather observations began in the 1940s in the Tanana River Valley of interior Alaska. For example, May 2004 was the wettest May on record at Fairbanks and the eighth wettest on record at Delta Junction. Although 57 mm of precipitation was received at the experimental site during May 2004, the 20 mm of precipitation that occurred from six events (the single greatest event was 5.1 mm on May 29) between the time of sowing and measuring soil properties likely altered the soil properties due to raindrop impact and wetting and drying.

Tillage management influenced cumulative and steady-state infiltration. Cumulative infiltration over 1 h varied from 77 mm for intensive tillage to 122 mm for autumn chisel plow whereas steady-state infiltration varied from 41 mm h^{-1} for intensive tillage to 82 mm h^{-1} for chisel plow (Table 1). These steady-state infiltration

Table 1
Cumulative and steady-state infiltration and saturated hydraulic conductivity at the end of 20 years (Spring 2004) of tillage and straw management practices in interior Alaska

Tillage/Straw	Infiltration		Hydraulic conductivity (10^{-5} m s^{-1})[a]
	Cumulative (mm)	Steady state (mm h^{-1})	
Intensive	77	41	12.6
Autumn chisel	122	82	19.4
Spring disk	86	60	14.9
No-tillage	91	70	23.2
LSD (0.05)	16	15	5.0
Straw/stubble	104	73	18.0
No straw/stubble	84	54	17.0
LSD (0.05)	12	10	ns

[a] Measured in the upper 0.05 m of the soil profile.

rates are comparable to those found by Freebairn et al. (1989) 1 year after establishing tillage treatments on a silt loam in Minnesota and by Arshad et al. (1999) 12 years after establishing tillage treatments on a silt loam in northern British Columbia, Canada. Although steady-state infiltration in no tillage exceeded that in intensive tillage, infiltration in no tillage did not exceed that in spring disk or autumn chisel plow. Previous studies reported that infiltration was greater for no tillage as compared with more intensive tillage practices due to greater macroporosity or pore continuity in no tillage (Ehlers, 1975; Logsdon et al., 1990). For example, Arshad et al. (1999) found that infiltration was greater in no tillage as a result of more continuous preferential flow channels than in conventional tillage in Canada. Anken et al. (2004) also found that preferential flow channels were more continuous, even though macroporosity was smaller, after nine years of no tillage versus moldboard plow or chisel plow in Switzerland. Others have reported that tillage generally decreases the stability, number, or continuity of preferential flow channels or macropores (Thomas and Phillips, 1979; Roseberg and McCoy, 1992; Shipitalo and Protz, 1987). The similarity in steady-state infiltration between no tillage and spring disk or autumn chisel plow suggests that no tillage has had little impact on the continuity, tortuosity, or number of macropores or preferential flow channels near the soil surface in this study. Although Sharratt et al. (2006) found no differences in porosity (i.e., bulk density) in the upper 50 mm of the soil profile among these tillage treatments, macropores still may have been more numerous or continuous in no tillage as a result of enhanced fauna activity in soils subject to no tillage (Ehlers, 1975; Lee, 1985; Mackay and Kladivko, 1985). In interior Alaska, there is little macrofaunal activity in agricultural soils (presumably due to extreme soil temperatures or prolonged duration that soils are frozen during winter) and thus existence of biopores in subarctic soils are likely limited to root channels. We recognize, however, that wetting and drying and freezing and thawing can be a significant process in cold regions whereby preferential flow channels such as cracks are formed in soils (Beven and Germann, 1982). Thus, even though no tillage may promote or preserve preferential flow channels or macroporosity in soils, other surface or subsurface characteristics in no tillage may have constrained infiltration. One characteristic that may restrict infiltration in no tillage is the presence of an organic layer overlying the mineral soil. Partially and well decomposed organic material (hemic and sapric material) have hydraulic conductivities on the order of 10^{-6}–10^{-7} m s^{-1} (Boelter, 1965, 1969; Dasberg and Neuman, 1977) which is much lower than that of the soil at the experimental site (Table 1). Thus, while no tillage may have promoted the development of soil structure or macroporosity that enhances infiltration, the formation of an organic layer on the soil surface, which was not observed 14 years ago (Sharratt, 1996), may have restricted water flow and retarded steady-state infiltration. The importance of this organic layer in apparently regulating soil hydrological processes has important implications for crop production. Thickening of this organic layer in the future may further restrict infiltration and diminish recharge of the soil profile. Thus, the sustainability of no tillage in this subarctic environment will depend upon a more complete understanding of the hydrological and thermal characteristics of this layer.

Cumulative and steady-state infiltration were also influenced by straw management (Table 1). Cumulative infiltration over one hour was 20 mm greater where straw was retained on rather than removed from the soil surface. In addition, steady-state infiltration ranged from 54 mm h^{-1} for the no straw and stubble treatment to 73 mm h^{-1} for the straw and stubble treatment. Retaining straw on the soil surface after harvest likely enhanced infiltration due to the creation of preferential flow channels along the side wall of incorporated straw elements that protrude from the soil surface or by dissipating the energy of raindrops and thus minimizing soil crust formation (Unger et al., 1991).

Soil water retention was influenced by tillage treatments as illustrated by the temporal variation in soil water content following the infiltration of surface water (Fig. 1). Soil water content within 48 h after infiltration of surface water was typically greater for no tillage as compared with other tillage treatments. Differences among treatments, however, became more apparent with time. Immediately after infiltration of

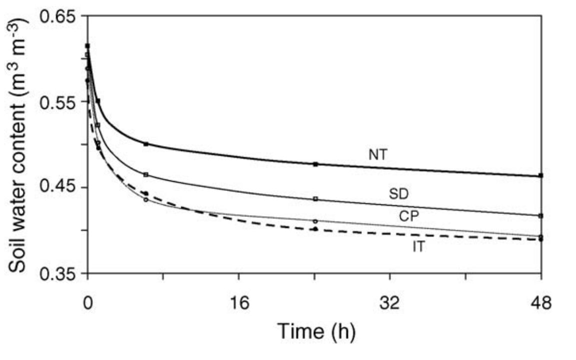

Fig. 1. Soil water content as a function of time after infiltration of surface water in no tillage (NT), spring disk (SD), autumn chisel plow (CP), and intensive tillage (IT). Water content was measured in the upper 100 mm of the profile in spring 2004 near Delta Junction, Alaska.

Table 2
Soil water content immediately and 48 h after infiltration of surface water and associated water loss as affected by tillage and straw management practices in interior Alaska

Tillage/Straw	Soil water content ($m^3\ m^{-3}$)		Water loss (mm)[a]
	0 h	48 h	
Intensive	0.57	0.39	18
Autumn chisel	0.59	0.39	20
Spring disk	0.60	0.41	19
No-tillage	0.61	0.46	15
LSD (0.05)	0.02	0.02	2
Straw/stubble	0.60	0.42	18
No straw/stubble	0.58	0.40	18
LSD (0.05)	0.01	0.01	ns

[a] Water loss was determined as the difference in soil water content 0 and 48 h after infiltration of surface water over a 100 mm depth.

surface water, for example, soil water content for the no tillage and spring disk treatments exceeded that of the intensive tillage treatment (Table 2). Then, from six to 48 h after infiltration, soil water content ranked as follows: no tillage > spring disk > chisel plow = intensive tillage (Table 2). These differences in soil water content may have been associated with dissimilarities in soil structure or pore size distribution among tillage treatments since soil structure and pore size distribution influence soil water retention of moist soils (Hillel, 1982). Indeed, Arshad et al. (1999) found that more water was retained in a silt loam subject to no tillage as a result of a smaller pore size distribution as compared with other tillage treatments in northern British Columbia, Canada. Factors other than pore size distribution, however, may have also influenced soil water retention. For example, hydraulic conductivity and hydraulic potential gradient also govern the temporal variation in soil water content according to:

$$\partial\theta \cdot \partial t^{-1} = \partial(K \cdot \partial h/\partial z)\partial z^{-1} \tag{1}$$

where θ is the soil water content ($m^3\ m^{-3}$), t, the time (s), K, the hydraulic conductivity ($m\ s^{-1}$), h, the hydraulic potential (m), and z is the depth (m). Differences in soil water content may then be due to differences in hydraulic conductivity and hydraulic potential gradient among tillage treatments. Although no tillage had a higher hydraulic conductivity than spring disk and intensive tillage (Table 1), the hydraulic conductivity of the organic layer in no tillage was presumably lower than that of mineral soil. While a low hydraulic conductivity would promote retention of water in the organic layer, a high hydraulic conductivity would allow water to dissipate more readily in mineral soil. Differences in hydraulic potential gradient likely occurred among tillage treatments as the soil water content prior to infiltration was 0.31 $m^3\ m^{-3}$ in no tillage, 0.14 $m^3\ m^{-3}$ in spring disk, and 0.13 $m^3\ m^{-3}$ in chisel plow and convention tillage (LSD = 0.02 $m^3\ m^{-3}$). Assuming that differences in soil water content among treatments extended below a depth of 100 mm, the hydraulic potential gradient would likely be smaller and therefore more water would be retained after infiltration of surface water in no tillage as compared with other tillage treatments. Therefore, despite the added complexity of the organic layer in ascertaining the cause of differences in water retention among tillage treatments, our reasoning suggests that the smaller pore size distribution, lower hydraulic conductivity of the organic layer that has formed over the mineral soil, or the antecedent wetness of the soil profile promoted the retention of water in no tillage compared with other tillage treatments.

Soil water retention was also influenced by straw management as indicated by differences between treatments in soil water content after infiltration of surface water (Table 2). Retaining straw and stubble on the soil surface after harvest resulted in wetter soils compared with removing straw and stubble from the soil surface. Straw can either act as a barrier to minimize evaporation when retained on the soil surface or may influence porosity when incorporated into the soil. Since evaporation was prevented by covering the soil surface with plastic in this study, straw influenced soil water retention as a result of altering soil porosity. Straw management, however, did not affect soil water loss within 48 h from the time surface water infiltrated the soil surface (Table 2). This finding suggests that the pore sizes created by the addition of straw to the soil were uniform and equally effective at retaining water over the range in matric and gravitational forces experienced over the 48 h observation period.

The temporal variation in soil water content (Fig. 1) indicates that water loss was not as rapid after the infiltration of surface water for no tillage as compared with other tillage treatments. This is substantiated by the differences in slope estimates of the log-transformed water content – time relationship. Slope estimates were −0.046 (S.E. = 0.002) for no tillage, −0.060 (S.E. = 0.002) for spring disk, −0.064 (S.E. = 0.001) for intensive tillage, and −0.067 (S.E. = 0.003) for chisel plow. Water loss from the upper 100 mm of the profile resulting from gravitational and soil matric forces over 48 h was 15 mm for no tillage and at least 18 mm for other tillage treatments (Table 2).

Saturated hydraulic conductivity was influenced by tillage and varied from $12.6 \times 0^{-5}\ m\ s^{-1}$ for intensive tillage to $23.2 \times 10^{-5}\ m\ s^{-1}$ for no tillage (Table 1).

Hydraulic conductivity was not affected by straw management practices. These results are similar to those found 14 years ago (Sharratt, 1996) in which the hydraulic conductivity of no tillage exceeded that of intensive tillage. These differences in hydraulic conductivity suggest the existence of structural dissimilarities in the upper 50 mm of the soil profile. Indeed, the higher conductivity of no tillage suggests greater porosity or pore continuity in no tillage versus intensive tillage. Since porosity (i.e., bulk density) did not differ among tillage treatments (Sharratt et al., 2006), we believe the high conductivity was caused by better continuity, less tortuous, or a greater number of preferential flow channels or macropores in soil subject to no tillage.

4. Conclusions

Small grains (e.g., barley) are well adapted to the semi-arid region of interior Alaska. Tillage and straw management practices can, however, have important implications regarding the sustainability of cropping systems because management practices can affect wind erosion and soil hydrologic characteristics.

A long-term tillage and residue management study was initiated in 1983 on a silt loam to identify sustainable practices for small grain cropping systems in interior Alaska. After 20 years, the soil had higher saturated hydraulic conductivity and retained more water against gravitational and matric forces when subjected to no tillage versus intensive tillage. The higher saturated hydraulic conductivity was apparently caused by greater macroporosity or more preferential flow channels whereas enhanced retention of water was likely caused by an organic layer overlying mineral soil or smaller hydraulic gradients in no tillage. Infiltration was greater in autumn chisel plow than in other tillage practices and appeared to be suppressed in no tillage by the overlying organic layer. The development of this organic layer in the past 14 years, as well as lack of weed control strategies, suggests that continuous no tillage is not yet a sustainable management practice as this layer has important ramifications for the soil hydrological and thermal environment. Therefore, minimum tillage (i.e., autumn chisel plow or spring disk) that incorporates straw left on the soil surface after harvest appears to be a viable management option for maximizing infiltration in interior Alaska.

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